A new grouping measure for evaluation of machine-component matrices

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The machine-component matrix is the main input to most machine-component grouping models used in cellular manufacturing. A number of measures have been developed for performance evaluation of machine-component grouping algorithms. In this paper, the relationship between these measures and the performance of the corresponding cellular manufacturing system is evaluated and a new grouping measure is developed which is more consistent in predicting the suitability of a manufacturing system for cellular manufacturing.

1. Introduction

The machine-component matrix is the main input to most machine component grouping models. It is an $M \times N$ matrix with zero/one entries. The presence or absence of a 'one' entry in row i and column j of the matrix indicates the operation, or lack of operation, of part j on machine i, respectively. When natural machine-component groups exist in a production system the rearrangement of parts and machines in the corresponding machine-component matrix generates a block diagonal form in which 'one' entries are concentrated in blocks along the diagonal of the matrix (Burbidge 1977). These blocks correspond to machine-component groups which are used to form a cellular manufacturing system. An initial machine-component matrix and its final block diagonal form are presented in Fig. 1.

A number of algorithms have been developed to identify machine-component groups for cellular manufacturing. Some of these algorithms form machine-component groups by permutations on rows and columns of the machine-component matrix (King and Nakornchai 1982, Chan and Milner 1982). Some other algorithms use clustering techniques from the field of numerical taxonomy to group machines into machine cells and components into part-families (McAuley 1972, Carrie 1973, Seifoddini and Wolfe 1986). The results of all of these algorithms can be presented in a block diagonal form. There are several studies that compare these algorithms (Mosier 1989, Chu and Tsi 1991, Miltenburg and Zhang 1991).

A complete block diagonal matrix in which mutually independent machine-component groups can be identified is ideal for the successful development of a cellular manufacturing system. As the number of parts requiring operations in more than one machine cell (exceptional parts) increases, the effectiveness of the corresponding cellular manufacturing system decreases. This is due to intercellular material handling costs associated with exceptional parts and the necessary adjustment in the cellular manufacturing system to accommodate the processing of these

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		Parts								
		1	2	3	4	5	6	7	8	9
M	A	1			1			1		
a	B						1		1	1
c	C		1	1		1				
h	D						1		1	1
i	E		1	1		1				
n	F	1			1			1		
e	G	1			1			1		

		Parts								
		2	3	5	1	4	7	6	8	9
M	C	1	1	1						
a	E	1	1	1						
c	G				1	1	1			
h	A				1	1	1			
i	F				1	1	1			
n	B							1	1	1
e	D							1	1	1

Figure 1. (*a*) Initial machine-component matrix (*b*) Block diagonal form.

exceptional parts (Seifoddini 1989). Since the number of exceptional parts is a function of the number of off-diagonal 'one' entries in the machine-component matrix, the structure of the final machine-component matrix significantly affects the effectiveness of the corresponding cellular manufacturing system. For this reason, a number of grouping measures have been developed to evaluate the efficiency of block diagonal forms including: bond energy (BE) (McCormick *et al.* 1972), grouping efficiency (GE) (Chandrasekharan and Rajagopalan 1987), grouping efficacy (GC) (Kumar and Chandrasekharan 1990), and grouping capability index (GCI) (Hsu 1990). No study has been done to determine the relationship between these measures and the performance of the corresponding cellular manufacturing system.

In this paper, the effectiveness of the existing measures in predicting the performance of a cellular manufacturing system is evaluated and a new grouping measure will be developed which more consistently determines the efficiency of a block diagonal form for developing a cellular manufacturing system.

2. Background

One of the first algorithms for converting a binary matrix into a block diagonal form uses a grouping measure called 'bond energy' (BE) (McCormick *et al.* 1972). This measure is calculated as follows:

$$\mathrm{BE} = \sum_{i=1}^{m} \sum_{j=1}^{n} d_{ij}[d_{i,j+1} + d_{i,j-1} + d_{i-1,j} + d_{i+1,j}]$$

where

m = number of rows in the binary matrix
n = number of columns in the binary matrix
d_{ij} = a binary (zero or one) entry in row i and column j of the binary matrix
$d_{o,j} = d_{m+1,j} = d_{i,0} = d_{i,n+1} = 0$

Since this measure is usually at its maximum value when the desirable block diagonal form is achieved, it can be used for the evaluation of machine-component matrices.

Grouping efficiency (GE) was developed to evaluate the efficiency of block diagonal matrices (Chandrasekharan and Rajagopalan 1987). It is defined as:

$$\mathrm{GE} = qE_1 + (1 - q)E_2$$

where

$$E_1 = \frac{\text{Number of ones in the diagonal blocks}}{\text{Total number of elements in the diagonal blocks}}$$

$$E_2 = \frac{\text{Number of zeros in the off-diagonal blocks}}{\text{Total number of elements in the off-diagonal blocks}}$$

$$q = \text{A weighting factor ranging between zero and one}$$

The selection of q for grouping efficiency is arbitrary and according to the designer of the measure (Kumar and Chandrasekharan 1990) the range of values for this measure is limited to 75–100%. That means even when there are a large number of exceptional parts, the grouping efficiency of the machine-component matrix is at least 0·75.

To overcome the problems of the selection of q and the limited range of grouping efficiency, another grouping measure has been developed. This measure is grouping efficacy (GC) and is defined as (Kumar and Chandrasekharan 1990):

$$GC = q \cdot E_1 + (1 - q)E_2$$

in which

$$q = \sum_{r=1}^{K} M_r \cdot N_r / m \cdot n$$

$$E_1 = \frac{e_o}{\sum_{r=1}^{K} M_r \cdot N_r}$$

$$E_2 = 1 - \frac{e_o}{m \cdot n - \sum_{r=1}^{K} M_r \cdot N_r}$$

where

K = number of blocks
M_r = number of rows in rth block
N_r = number of columns in rth block
e_o = number of ones in the diagonal blocks
m and n as defined before.

Grouping efficacy overcomes the problem of grouping efficiency by incorporating the size of the matrix into the calculation of the measure. It also provides a quantitative basis for calculating the weighting factor, q.

In a study by Hsu (1990), it was shown that neither group efficiency nor group efficacy is consistent in predicting the performance of a cellular manufacturing system based on the structure of the corresponding machine-component matrix.

Grouping capability index (GCI) (Hsu 1990), is defined as:

$$GCI = 1 - \frac{e_o}{e}$$

where

e_0 = number of exceptional elements in the machine-component matrix
e = total number of one entries in the machine-component matrix

Contrary to the previous two measures, GCI excludes zero entries from the calculation of grouping efficiency.

In addition to machining requirements of parts which are given in the machine-component matrix, many other production factors such as production volume and processing times of operations affect the performance of a cellular manufacturing system. None of the previously discussed measures consider these factors. In this paper, a new grouping measure is defined which is based on machining requirements of parts, production volume and processing times of operations.

3. New grouping measure

The new grouping measure called 'quality index' (QI) is calculated as the ratio of the intercellular workload to the total plant's workload. The intercellular workload (ICW) is defined as:

$$\mathrm{ICW} = \sum_{l=1}^{K}\left[\sum_{i=1}^{M} X_{il}\left(\sum_{j=1}^{N}(1 - y_{jl})\mathrm{Z}_{ij}\cdot \mathrm{V}_j \cdot \mathrm{T}_{ij}\right)\right]$$

where

$$\mathrm{X}_{il} = \begin{cases} 1 & \text{if machine } i \text{ is assigned to machine cell } l \\ 0 & \text{otherwise} \end{cases}$$

$$\mathrm{Y}_{jl} = \begin{cases} 1 & \text{if part } j \text{ is assigned to machine cell } l \\ 0 & \text{otherwise} \end{cases}$$

$$\mathrm{Z}_{ij} = \begin{cases} 1 & \text{if part } j \text{ has operations on machine } i \\ 0 & \text{otherwise} \end{cases}$$

V_j = production volume for part j

T_{ij} = processing time of part j on machine i

K, M, and N = number of machine cells, machines, and parts, respectively

The total plant workload (PW) can be calculated as:

$$\mathrm{PW} = \sum_{i=1}^{M}\sum_{j=1}^{N} Z_{ij}\cdot \mathrm{V}_j \cdot \mathrm{T}_{ij}$$

where

M, N, Z_{ij}, V_j and T_{ij} are as defined before.

The quality index (QI) for a block diagonal machine-component matrix is calculated as:

$$\mathrm{QI} = 1 - \frac{\mathrm{ICW}}{\mathrm{PW}}$$

By incorporating the production volume and processing times in the calculation of grouping measure, QI has the potential for significantly improving the evaluation of block diagonal forms. This is due to the fact that production volume and processing time are two important factors affecting the performance of the cellular manufacturing system. As a result, QI is more closely related to the performance of the cellular manufacturing system than all other grouping measures which solely use the data in the machine-component matrix.

4. Comparison of grouping measures

A simulation model is developed for the performance evaluation of cellular manufacturing systems. The performance evaluation is the basis for the comparison of the five different grouping measures defined here. It is used to determine which measure more accurately predicts the performance of a cellular manufacturing system by evaluating the corresponding machine-component matrix. The efficiency of a machine-component matrix is calculated using different grouping measures. The performance of the corresponding cellular manufacturing system is then determined using performance measures such as average flow time and average in-process inventories. Finally, based on the relationship between the value of the grouping measure of the machine-component matrix and the performance of the corresponding cellular manufacturing system, the effectiveness of each grouping measure is evaluated.

The algorithmic form of the procedure for the evaluation of grouping efficiency measures is as follows:

Step (1) Choose a machine-component matrix and convert it into a block diagonal form using one of the existing machine-component grouping algorithms such as ROC (King and Nakoranchai 1982), DCA (Chan and Milner 1982), or SCM (Seifoddini and Wolfe 1986).

Step (2) Calculate the efficiency of the block diagonal form using grouping measures including: bond energy (BE), grouping efficiency (GE), grouping efficacy (GC), grouping capability index (GCI), and quality index (QI).

Step (3) Develop a simulation model of the cellular manufacturing system corresponding to the block diagonal form obtained in Step 1.

Step (4) Estimate the average flow time and average in-process inventories for the cellular manufacturing system using the simulation model developed in Step 3.

Step (5) Repeat Steps 1–4 for a number of different situations and evaluate the relationship between each grouping measure and the performance of the corresponding cellular manufacturing system.

This procedure will be used in the following section to compare the existing grouping measures.

The simulation model for the performance evaluation of the cellular manufacturing system has the following characteristics:

- The machine-component matrix used to form the cellular manufacturing system is given in Fig. 2.
- The time between orders for parts is exponentially distributed with the mean of 10 hours. The size of each order has a uniform distribution between 1–10 parts.
- The processing and set-up times are deterministic (data from a real shop is used).
- Set-up times are sequence dependent. Set-up times for parts within a part-family are half of those for parts from two different part-families. This ratio decreases to 0·1 when two identical parts visit a machine in row.
- The processing and transportation of parts between machine cells is done in batches. Within a machine cell, parts are transferred to the next machine as soon as they are processed on the current machine.

		Parts										
		1	2	3	4	5	6	7	8	9	10	11
M	1			1				1				1
a	2	1	1				1			1		
c	3	1	1				1			1		
h	4				1	1			1		1	
i	5			1				1				1
n	6			1				1				1
e	7				1	1			1		1	

(*a*) Initial machine-component matrix.

		Part Families										
		1	2	6	9	3	7	11	4	5	8	10
M	2	1	1	1	1							
a	3	1	1	1	1							
c	1					1	1	1				
h	5					1	1	1				
i	6					1	1	1				
n	4								1	1	1	1
e	7								1	1	1	1

(*b*) Block diagonal form.

Figure 2. Machine-component matrix used in simulation model.

- The average flow time and in-process inventories are used as the performance measures for the cellular manufacturing system.

The simulation model is used to estimate the two performance measures: average flow time and average in-process inventories. A warm-up period of six months is used to minimize the effects of the transient period. A common graphical method known as replication/deletion method was used to determine the length of warm-up period. Visual examination of the graph shows that system performance reaches the steady state in six months. Therefore a warm-up period equal to six months was considered and all observations recorded during that period were truncated.

The model is simulated over a period of one year beyond the warm up period. A method called batching the data is suggested in simulation texts as a technique for constructing a point estimate and confidence interval for the mean. Based on batching method the data generated during steady state condition are divided into n batches of size k. In this study the data were divided into 20 batches of size 13 days (equal almost to one year excluding holidays). It is reasonable to divide the observations from a single long simulation run into 10 to 20 batches (Law and Kelton 1982).

In order to minimize the variance of the mean of differences common random number streams were employed across the simulation models. That is, the same stream was used to generate the time between orders and size of orders for all versions.

5. Analysis of results

To evaluate the relationship between the values of grouping measures: BE, GE, GC, GCI and QI, and the performance of the cellular manufacturing system, five different versions of the machine-component chart in Fig. 2 are used in the simulation experiment. Variations from one version to another are limited to changes in the number of exceptional parts and their processing requirements.

In the following sections, each version of the machine-component matrix and the associated simulation results are presented. In addition, a frequently cited machine-component matrix in the literature will be used to calculate the efficiency measures and to estimate (using simulation) the performance of the corresponding cellular manufacturing system. This provides a common basis for comparing the results of the study with the existing results.

In version 1 (Fig. 3(*a*)), there are three machine cells with no exceptional parts. As expected, in this case, all grouping measures yield 100% efficiency. The values of these measures and the corresponding simulation results are given in Fig. 3(*b*). It should be noted that all grouping measures except BE are in the scale of 0–1·0. In order to present the BE in the same scale, the value of BE for the ideal machine-component matrix is considered equal to 1·0. Then the value of BE for other versions of the matrix is divided by the value of the ideal matrix. For example, assume the ideal matrix yields BE equal to 64 and another version of the matrix yields BE equal 59. Then the adjusted value of BE for the ideal matrix is $64/64 = 1{\cdot}0$, and for the latter matrix is $59/64 = 0{\cdot}92$.

Machines	Parts: 1	2	6	9	3	7	11	4	5	8	10
2	1	1	1	1							
3	1	1	1	1							
1					1	1	1				
5					1	1	1				
6					1	1	1				
4								1	1	1	1
7								1	1	1	1

(*a*) Block diagonal form.

Matrix efficiency				
BE	GE	GC	GCI	QI
1	1	1	1	1

Shop performance	
Flow time	Work-in-progress
35	19

(*b*) Grouping measures and simulation results.

Figure 3. Version 1 of the machine-component matrix.

Machines	Parts: 1	2	6	9	3	7	11	4	5	8	10
2	1	1	1	1							
3	1	1	1	1							
1					1	1	1				
5					1	1	1				
6					1	1	1				
4								1	1	1	1
7								1	1	1	1

(*a*) Block diagonal form.

Matrix efficiency				
BE	GE	GC	GCI	QI
0·93	0·97	0·92	0·96	0·99
Shop performance				
Flow time		Work-in-progress		
38		19		

(*b*) Grouping measures and simulation results.

Figure 4. Version 2 of the machine-component matrix.

Version 2 (Fig. 4(*a*)) is slightly different from version 1. Part 1, in this version, has one operation outside machine cell 1 and becomes an exceptional part. Since this part has the minimum workload content (processing time × volume), its effect on performance of the cellular manufacturing is minimal. This is reflected in simulation results in which the average flow time is marginally higher than in version 1 with no change in the average in-process inventories. All grouping measures are lower as presented in Fig. 4(*b*).

In version 3 (Fig. 5(*a*)), part 8 becomes an exceptional part (by switching one of its operations from machine 4 to machine 3). This part has the highest workload content and the change of its status should significantly change the performance measures as indicated by simulation results (Fig. 5(*b*)). Only one of the grouping measures, QI, reflects the changes dramatically. QI decreases from 0·99 in version 2 to 0·90 in this version. BE decreases from 0·93 to 0·90. All other measures are insensitive to changes introduced in version 3 and remain the same (Fig. 5(*b*)).

In version 4 (Fig. 6(*a*)), there are two exceptional parts (parts 1 and 5). These are parts with the lowest workload contents, and as expected have less adverse effect on the performance of the cellular manufacturing system than the single exceptional part in version 3. This is reflected in the value of QI which increases to 0·92 from 0·90 in the previous case. Other measures show deterioration in grouping efficiency (Fig. 6(*b*)). The performance measures in this version (Fig. 6(*b*)) show improvement which is consistent with the increase in QI.

Parts

Machines	1	2	6	9	3	7	11	4	5	8	10
2	1	1	1	1							
3	1	1	1	1						1	
1					1	1	1				
5					1	1	1				
6					1	1	1				
4								1	1		1
7								1	1	1	1

(*a*) Block diagonal form.

Matrix efficiency				
BE	GE	GC	GCI	QI
0·90	0·97	92	0·96	0·99

Shop performance	
Flow time	Work-in-progress
78	40

(*b*) Grouping measures and simulation results.

Figure 5. Version 3 of the machine-component matrix.

Finally, in version 5, two exceptional elements were created (Fig. 7(*a*)) but in this case the two operations with the largest workload contents are relocated (operations of part 6 on machine 2 and part 4 on machine 7). It was expected that the heavier intercellular workload created by these two new exceptional elements would lead to further deterioration in shop performance. The results of the simulation runs show a drastic change in all performance measures (Fig. 7(*b*)). QI criteria performed accordingly and showed a drop in efficiency of the matrix from 0·96 to 0·78. All other measures showed no change in efficiency in spite of change in shop performance.

5.1. *Graphical comparison of results*

Based on the results obtained by the five versions of machine-component matrix, the values of efficiency measures versus the shop performances are plotted in Fig. 8. As this figure illustrates, the mean flow time increases as the efficiency of machine-component matrix decreases. The graph of QI consistently follows such a relationship while GE, GC, GCI and BE have a mixed pattern.

5.2. *Test of hypothesis*

To draw a statistical conclusion on goodness of proposed QI measure a test of hypothesis was conducted which is defined as follows:

H_{01}: No difference exists, between mean flow time at different levels of QI.
H_{02}: No difference exists, between mean work-in-process (WIP) inventory at a different level of QI.

Machines		Parts										
		1	2	6	9	3	7	11	4	5	8	10
	2	1	1	1	1							
	3		1	1	1							
	1					1	1	1		1		
	5					1	1	1				
	6				1	1	1	1				
	4	1							1		1	1
	7								1	1	1	1

(*a*) Block diagonal form.

Matrix efficiency				
BE	GE	GC	GCI	QI
0·84	0·94	0·85	0·92	0·92

Shop performance	
Flow time	Work-in-progress
43	19

(*b*) Grouping measures and simulation results.

Figure 6. Version 4 of the machine-component matrix.

Rejection of H_{01} and H_{02} implies that the performance of cellular manufacturing is significantly sensitive to the change in efficiency of machine-component matrix.

Table 1 shows the 95% confidence intervals of the steady state mean flow time and WIP inventory for 5 cases under study.

From the table, the estimates of the mean flow time (F_i) and mean WIP inventories appear to be somewhat different from one version to another. To see if this difference is statistically significant a paired-t test confidence interval (Djassemi 1994) was used and the results are summarized in Tables 2 and 3.

From Table 2, the null hypothesis ($H_0 1$) concerning the difference between version 1 and 2 in terms of mean flow time was accepted at the 5% level of significance. In other words, these two versions have been very close in the job's mean flow times. The efficiency of corresponding machine-component matrices in terms of QI were 1 and 0·99 respectively which explains the close performance of the two versions.

The null hypothesis was rejected in the remaining cases indicating that means flow times were not equal between versions 2 and 3, 3 and 4, and 4 and 5. There is an explanation for this result. That is, changes in QI level have a significant impact on mean flow time while changes in other efficiency measures did not show the same effect and even in some cases did not show any effect.

Table 3 shows the results of the test of hypothesis on WIP inventory. The inferences of the results led to acceptance of null hypothesis H_{02} concerning the mean difference between version 1 and 2 in terms of WIP. When the QI level remained unchanged from version 1 to version 2, the shop performance reacted correctly. That is, WIP inventory remained unchanged. The null hypothesis for mean difference of

Machines	Parts: 1	2	6	9	3	7	11	4	5	8	10
2	1	1		1							
3	1	1	1	1				1			
1					1	1	1				
5					1	1	1				
6					1	1	1				
4			1					1	1	1	1
7									1	1	1

(*a*) Block diagonal form.

Matrix efficiency				
BE	GE	GC	GCI	QI
0·84	0·94	0·85	0·92	0·78

Shop performance	
Flow time	Mean work-in-progress
67·2 Hr	33 Parts

(*b*) Grouping measures and simulation results.

Figure 7. Version 5 of the machine-component matrix.

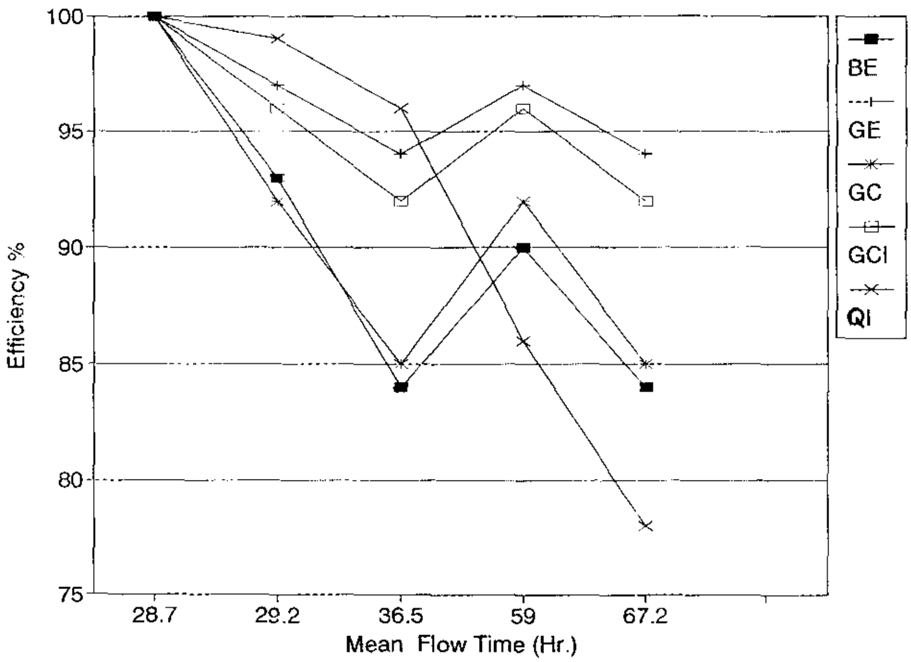

Figure 8. Valves of grouping measures versus mean flow time.

versions 3 and 2, 3 and 4, 5 and 4 was rejected, indicating that the changes in QI level has significant impact on mean WIP inventories in the cellular manufacturing shops.

As expected, the above results indicate that only QI among the grouping measures is sensitive to changes in workload content of parts in a cellular manufacturing system. Since workload content is more closely related to the performance of a cellular manufacturing system, QI is a more effective grouping efficiency measure than other measures discussed in the literature. This is confirmed by simulation results which are consistent with QI values.

To provide a common basis for the comparison of grouping measures, a frequently cited machine-component matrix will be used to calculate different grouping measures and to generate the simulation results. The final machine-component matrix with 16 machines and 43 parts is given in Fig. 9 (Burbidge 1977). The grouping measures and simulation results for this machine-component matrix and a modified form of it (in the modified form three machines: 6, 8 and 10 have been duplicated) are given in Fig. 10. The modified machine-component matrix is presented in Fig. 11. The results reinforce the conclusions drawn from the previous simple example and provide further support to the idea of using grouping measures for performance evaluation in cellular manufacturing systems.

Matrix version	Mean flow time (F_i)	CI 95%	Mean WIP (W_i)	Ci 95%
1	28·7	22·7–34·6	13·2	9·05–17·7
2	29·2	23·4–34·9	13·4	9·29–28·5
3	59	41·8–77·3	29	18·6–41·2
4	36·5	28·8–44·1	17·0	12·0–22·1
5	67·2	47·3–87·0	33	21·9–44·2

Table 1. Means and confidence intervals of flow time and WIP.

Mean difference	CI, 95%	Test of hypothesis
F_2-F_1	0·512 ± 0·531	Accept H_{o1}
F_3-F_4	30·4 ± 17.5	Reject H_{o1}
F_3-F_4	23·1 ± 15·2	Reject H_{o1}
F_5-F_4	30·7 ± 19·3	Reject H_{o1}

Table 2. Results of test of hypothesis for mean flow time.

Mean difference	CI, 95%	Test of hypothesis
W_2-W_1	0·167 ± 0·232	Accept H_{o2}
W_3-W_2	16·7 ± 8·62	Reject H_{o2}
W_3-W_4	3·84 ± 2·34	Reject H_{o2}
W_5-W_4	19·8 ± 8·81	Reject H_{o2}

Table 3. Results of test of hypothesis for mean WIP.

Parts

Machines	2	4	7	10	18	28	32	37	38	40	42	1	5	6	8	9	11	12	14	15	16	19	20	21	23	29	31	33	34	39	41	43	17	35	36	13	25	26	3
2	1			1		1	1	1	1	1	1																												
9	1	1		1	1	1	1	1	1	1	1																												
16	1		1	1	1		1	1	1		1																												
1								1			1																												
5													1		1	1			1	1	1	1		1	1	1		1			1	1							
15													1						1			1		1				1			1	1							
4													1			1			1			1		1	1	1													
6	1		1				1	1		1	1	1		1	1			1	1			1			1			1	1	1		1	1			1			
8	1					1		1	1			1			1	1	1	1		1		1	1	1	1		1				1	1							1
3			1																										1				1	1	1				
14	1													1																			1	1					
7												1																								1	1		
10												1						1								1				1						1	1	1	
11																1							1																1
12																	1																						
13																																							1

Figure 9. Block diagonal form for 16 machines and 43 parts.

Case	GE	GC	GCI	BE	QI	Flow time	WIP
1	0·73	0·45	0·78	0·80	0·61	21 Hr.	17
2	0·75	0·46	0·90	0·82	0·86	20 Hr.	13

Figure 10. Efficiency and performance measures for Burbidge's problem.
Case 1. Cellular manufacturing without machine duplication.
Case 2. Cellular manufacturing with machine duplication.

		2	4	7	10	18	28	32	37	38	40	42	1	5	6	8	9	11	12	14	15	16	19	20	21	23	29	31	33	34	39	41	43	17	35	36	13	25	26	3	22	24	27	30
	2	1			1	1	1	1	1	1	1	1																																
	9	1	1		1	1	1	1	1	1	1	1																																
	16	1		1	1	1		1	1	1		1																																
	1								1			1																																
M	6	1		1				1	1		1	1																																
A	8	1					1		1	1																																		
C	5													1		1	1			1	1	1	1		1	1	1		1			1	1											
H	15													1						1			1		1				1			1	1											
I	4													1			1			1			1		1	1	1																	
N	6												1		1	1			1	1			1			1			1	1	1		1	1			1							
E	8												1			1	1	1	1		1		1	1	1	1		1				1	1							1				
S	10												1						1									1			1													
	3			1																										1				1	1	1								
	14	1													1																			1	1									
	7												1																								1	1						
	10																																				1	1	1					
	11																1							1																1		1	1	1
	12																	1																							1	1	1	1
	13																																							1		1		

Figure 11. Machine-component matrix with three machines duplicated.

6. Conclusions

Simulation modelling was used to determine the relationship between values of grouping measures and the performance of the corresponding cellular manufacturing system. Five different grouping measures were compared based on the simulation results. The study shows that grouping measures when properly defined can predict the performance of the corresponding cellular manufacturing system. Based on the simulation results, the newly defined grouping measure, QI, is more effective than other measures because it is more closely related to the performance of the cellular manufacturing system.

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